DOE/FOSSIL ENERGY'S FUEL CELL PROGRAM: STATUS AND FUTURE PLANS

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Abstract

The U.S. Department of Energy's Federal Energy Technology Center (FETC) manages the U.S. Fuel Cell Program to commercialize molten carbonate and solid oxide fuel cells. Molten carbonate fuel cells (MCFCs) are being developed by Energy Research Corporation (ERC) and M-C Power Corporation (MCP). After modifying their designs based on lessons learned during demonstrations in 1996 and 1997, ERC and MCP are initiating a new set of demonstrations to bring their technologies closer to the market.

Solid oxide fuel cells (SOFCs) are being developed by Siemens Westinghouse Power Corporation (SWPC). SWPC has recently completed testing of a 100 kW unit in a cogeneration configuration in the Netherlands and is preparing for a test of a hybrid (fuel cell/gas turbine) system at the National Fuel Cell Research Center in Irvine, California.

FETC also manages the Climate Change Fuel Cell Program. With funds provided by the Department of Defense, this program provides a rebate for installation and operation of commercial fuel cells. Since 1995, this program has supported the installation of numerous ONSI 200 kW phosphoric acid fuel cells.

Future plans for the Fuel Cell Program include the development of fuel cell/gas turbine hybrids and the initiation of the 21st Century Fuel Cell Program. The hybrid systems, with a goal of 70% efficiency, will be developed with support of the DOE Advanced Turbines Systems Program. The 21st Century Fuel Cell Program will take efficiency higher and reduce costs dramatically. The product of the 21st Century Fuel Cell Program will be a key enabling technology for the DOE Vision 21 Program.

Introduction

Fuel cell powerplants offer the potential for ultra-high efficiency energy conversion and the enhancement of the quality of the environment. Concerns for the global environment are driving future power generation systems toward technologies that produce extremely low environmental emissions. Because of their high efficiencies, fuel cell powerplants will help in reducing carbon dioxide emissions. Since combustion is not utilized in the process, fuel cells generate very low amounts of NO_x.

Fuel cell powerplants have been exempt from air permitting requirements in California and Massachusetts. The fuel cell is attractive for both urban and remote applications. It is ideal as a distributed generator; that is, it can be sited at or near the electricity user -- for example, at electrical substations, at shopping centers or apartment complexes, or in remote villages -- minimizing long-distance transmission lines.

In the United States, DOE/Fossil Energy's Fuel Cell Program is a cost-shared, market-driven program. As implemented by DOE/FETC, the Program emphasizes natural gas-powered stationary applications and currently supports fuel cell designs being developed by three U.S. firms. FETC also cooperates with the U.S. Department of Defense to implement the Climate Change Fuel Cell Program.

The future of the Fuel Cell Program will incorporate higher efficiencies, lower cost, and performance improvements through the use of fuel cell/gas turbine hybrids and the 21st Century Fuel Cell Program. Fuel cells will also be a key enabling technology of Fossil Energy's Vision 21 Program. As the Vision 21 powerplant matures, fuel cells will eventually be operated on coal gas.

Fuel Cell Program Status

Molten Carbonate Fuel Cells

Over the past several years, the primary focus of the Fuel Cell Program has been on the development of advanced high temperature fuel cells. These include molten carbonate fuel cells (MCFCs) and solid oxide fuel cells (SOFCs) that have the potential for efficiencies in the range of 50-70 percent and suitable for integration with a gas turbine in a hybrid configuration or a coal gasifier for Vision 21.

The two MCFC developers are Energy Research Corporation (ERC) and M-C Power Corporation (MCP). ERC is developing an externally manifolded, internally reformed MCFC and has constructed a 17-MW/year MCFC manufacturing plant. ERC has constructed a 400 kW test facility in Danbury, Connecticut, and has scaled up to a 8-square foot (0.74 square meter) area stack. The manufacturing facility demonstrated its capability by shipment of sixteen tall stacks in four modules for the Santa Clara 2-MW test unit, which began operation in the spring of 1996. This is the largest MCFC demonstration in the world and the largest fuel cell powerplant to operate in the United States. The 2-MW Santa Clara test unit reached full power and operated for over 3,000 hours.

Commercial size stack tests at the Danbury facility evolved from the Santa Clara experience and have been extremely successful. Tall stack testing in integrated test facilities at ERC, that simulated final product operating conditions, was successfully completed. Two 250 kW tall stacks have been tested. The first 250 kW stack was tested for over 2,500 hours with three thermocycles and no noticeable deterioration of performance. The other 250 kW stack is currently operating in a grid-connected mode. Performance and stack cost goals are being met through cell area scaleup and testing, efficient packaging, and component cost reduction through design manufacturing improvements. Stack module and balance-of-plant (BOP) improvements will be verified at a 300 kW scale.

The preliminary design of ERC's market-entry, 3-MW direct fuel cell powerplant has been completed. A conceptual installation of this system is shown in Figure 1. In response to market interest, ERC will also offer a 1-MW design. Further cross licensing arrangements with MTU of Germany has given ERC access to MTU's 250 kW product in the United States. Therefore, ERC will be able to offer products ranging in size from 250 kW to 3-MW. Performance characteristics and early production units (EPU's) have been identified. Projected capital costs are under $1,300/kW.

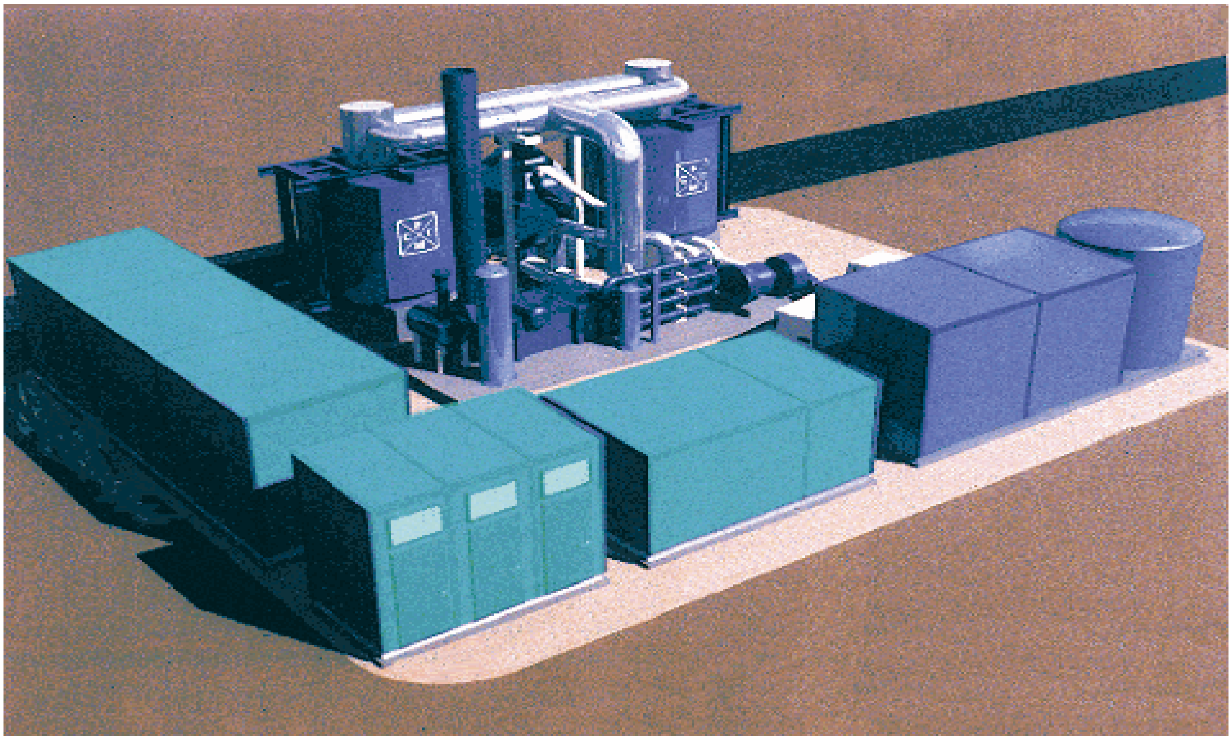

Figure 1: ERC 3-MW Direct Fuel Cell System

During the 1980's, the Institute of Gas Technology (IGT) invented the Internally Manifolded Heat Exchanger (IMHEX®) separator plate concept for MCFC's. The internal manifolding is used to distribute fuel and air to individual cells within the stack. This fundamental technology was transferred to MCP in 1989. Since that time, MCP has scaled up the technology from lab-scale (4 inches by 4 inches) size to commercial-scale dimension of 1 square meter for individual cells. The technology has been verified in 20 kW short stacks at the MCP testing facility and in a 250 kW demonstration plant. MCP's MCFC manufacturing plant in Burr Ridge, Illinois, has a capacity of assembling 4 MW/year of stacks.

The MCP test facility was constructed at the Naval Air Station Miramar, in San Diego, California, and began operation in January 1997. This plant demonstrated the functionality of a completely integrated 250 kW natural gas fueled MCFC powerplant cogeneration system under commercial operating conditions. Several technology improvements were contained in this unit, including a plate-type reformer specifically designed for MCFC systems. During the demonstration, the plant provided 156 MW-hours of electrical energy and over 385,000 pounds of steam to the base operations.

Based on a thorough post-test analysis of the 250 kW test unit stack, MCP modified its design and constructed a 75 KW stack for testing at Miramar. This 75 kW stack exhibited superior

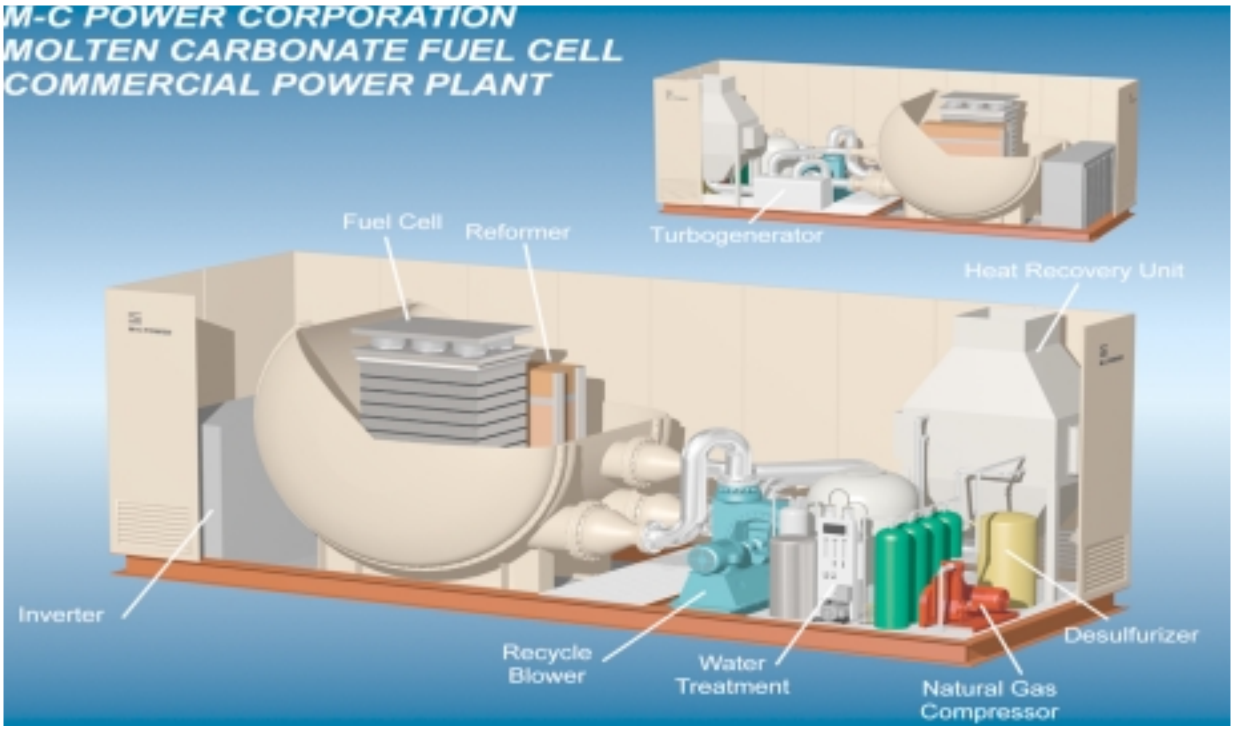

Figure 2: Artist's Concept of MCP's 500-kW MCFC Powerplant

sealing and performance in its acceptance tests at the MCP laboratories. The stack began generating power at Miramar in early July 1999, and the test is expected to continue until December 1999.

Based on relative costs of BOP equipment and supported by market research, MCP has increased the size of its market entry powerplant to 500 kW; and the artist's concept of this powerplant is shown in Figure 2.

Solid Oxide Fuel Cells

Siemens Westinghouse Power Corporation (SWPC) is the acknowledged world leader in tubular SOFC technology. SWPC is developing a tubular configuration that has been validated to a far greater extent than any other SOFC technology. Two thin-wall porous support tube cells have been on test for over 7 years (>69,000 hours). The tubes have been scaled up to a nominal

2 meters in length. The porous air support tube has been eliminated; the cell is now supported by the air electrode. SWPC completed 114 thermal cycles on 2 Air Electrode Supported (AES) cells which were 50-centimeter (cm) active length and used 2 Electrochemical Vapor Deposition (EVD) steps.

The Kansai Electric Company (Japan) tested a four-cell article and accumulated 10,529 hours of operation at high current densities and completed 101 thermal cycles. These cells were 150-cm

Figure 3: Siemens Westinghouse 100 kW EDB/ELSAM Unit

active length and used 2 EVD steps. In addition, the cells experienced only minor voltage degradation. Ontario Hydro has accumulated more than 1,725 hours of operation on a single 150-cm AES cell manufactured with two EVD steps. More than 1,475 of the 1,725 hours were operated at 5 atmospheres. This type of cell is typical of the cells that SWPC has used in the 100 kW demonstration unit in late 1997 and will be used in their commercial offerings.

Southern California Edison has operated a 25 kW unit at their High Grove Generating Station in Terrace, California. This unit was moved to the University of California and was restarted after two years of being stored in a warehouse. It has accumulated over 3,200 hours after the unit was restarted (8,800 hours total). SWPC completed testing of a 25 kW unit for the Joint Gas Utilities (JGU) at their Science and Technology Center at Pittsburgh, Pennsylvania, after completing over 13,000 hours of operation and surviving 10 thermal cycles. The 100 kW EDB/ELSAM unit

(Figure 3, courtesy of the Dutch Umbrella Association EnergieNed on behalf of the Energy Distribution Companies in the Netherlands) was completed in December 1997 and has completed 4,000 hours of operation and two thermal cycles.

SWPC has brought on line a 45,000-square foot Pilot Manufacturing Facility with a production capacity of 4 MW/year per shift. This facility completed cell production for a 250 kW Southern California Edison combined cycle unit in March 1998. SWPC appears to have eliminated two of the three EVD steps in manufacturing. They are currently working on the elimination of the last EVD step (for the electrolyte). To further reduce costs, SWPC is increasing the cell output by cell redesign and pressurized operation, testing low-cost air electrode material, and investigating low-cost air electrode manufacturing. Current cell life is estimated to be 10 years, with 7 years already demonstrated. SWPC believes cell life for commercial cells will be 10 to 20 years. Commercial product size will range from 1 to greater than 50 MW in a combined-cycle configuration.

Climate Change Fuel Cell Program

Market penetration of fuel cells is determined to a large extent by product costs. Increasing manufacturing volumes lowers product cost, leading to increased market penetration. Through an Interagency Agreement between FETC and the U.S. Department of Defense (DOD), DOD has provided funds for the Climate Change Fuel Cell Program. For several years, this program has supported the market penetration of fuel cells by a rebate of $1,000/kW or one-third of the total project costs, whichever is lower, to those organizations installing a fuel cell manufactured in the U.S. Priority has been given to powerplants placed at DOD installations.

In 1996, the Climate Change Fuel Cell Program was managed by FETC and resulted in 33 awards for the installation of 42 ONSI PC25, 200 kW phosphoric acid fuel cell (PAFC) powerplants. ONSI Corporation, a subsidiary of International Fuel Cells, located in South Windsor, Connecticut, has been actively involved in the development and marketing of on-site PAFC systems and has a 40 MW/year manufacturing facility.

In 1997, DOD again provided funds to reduce the costs of fuel cells by providing the same rebate opportunity. This program was managed by DOD’s Advanced Research and Development Engineering Center in Picatinny, New Jersey. Fifty-three awards for ONSI PC25 installations were made in the program in 1997.

In 1998, DOD provided funds ($5 million) to FETC to manage the Climate Change Fuel Cell Program. The DOD program management was provided through the Construction Engineering Research Laboratories (CERL). Awards were made twice in 1999 as a result of this funding from 1998. The first set of awards were for sixteen ONSI powerplants. Following the first set of awards, the qualification criteria were modified to lower the minimum fuel cell size from 100 kW to 3 kW. The second set of awards were for ninety 7-kW proton exchange membrane (PEM) fuel cells manufactured by PlugPower, sixteen 3-kW PEM units from American Power, and one 300 kW SOFC unit from SWPC. DOD anticipates additional funding in the FY2000 budget to continue this program.

Future Plans for the Fuel Cell Program

The Fuel Cell Program expects to increase efficiency and improve performance through the development of fuel cell/gas turbine hybrids and the initiation of the 21st Century Fuel Cell Program. One of the most promising developments in fuel cell powerplants is the conceptual development of very high efficiency fuel cell gas turbine powerplants. The hybrid fuel cell-turbine powerplant can configure the high- or intermediate-temperature fuel cell with a low-pressure ratio gas turbine. Electrical conversion efficiencies from 70 to over 80 percent are calculated for this type of system. Even higher efficiencies may be possible as the fuel cells are networked or staged and other refinements or advances are incorporated.

Fuel Cell/Gas Turbine Hybrids

Because of the synergistic effects leading to the higher efficiencies and lower emissions achieved by combining a fuel cell and a gas turbine into a power generation system, many potential system configurations have been developed. These systems are the logical extension of the DOE-funded fuel cell and gas turbine development and represent the most promising fossil energy powerplants ever conceived.

The typical hybrid system size is 3 to 20 MW. One promising configuration is the SOFC topper shown in Figure 4. By allowing the fuel cell in the powerplant to serve as the combustor for the gas turbine and the gas turbine to serve as the balance of plant for the fuel cells, the combined efficiency is raised to the 60 percent range even at sizes of less than 3 to 10 MW, and NO_x emissions are essentially eliminated.

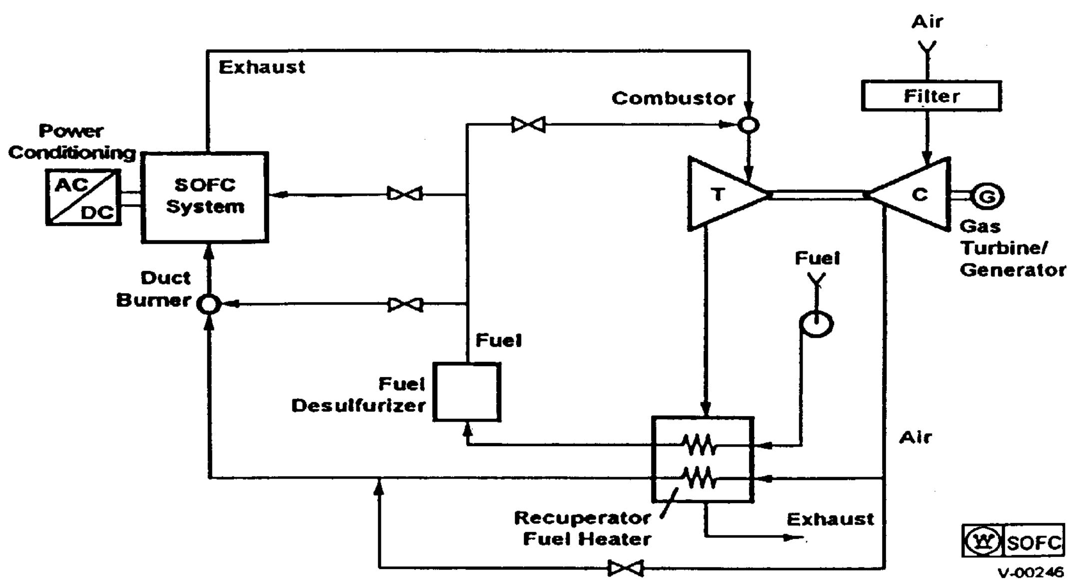

Figure 4: Example of a Fuel Cell/Gas Turbine Hybrid System Concept

In any system, conventional or hybrid, fuel cells may be networked, that is, placed in series rather than in parallel, increasing further the overall system efficiency. In this sense, a fuel cell can be bottomed by another fuel cell to further increase efficiency. New hybrid concepts promise over 80% and higher efficiency as the fuel cells are networked or staged.

From the results of the two U.S. workshops on high-efficiency fuel cell gas turbine hybrid systems, DOE solicited for conceptual hybrid systems involving fuel cells and gas turbines. Five awards were made in FY99 to the teams in Table 1.

Table 1: Fuel Cell/Gas Turbine Hybrid Design Teams

Fuel Cell Team Member	**Gas Turbine Team Member**
Siemens Westinghouse Power Company	Rolls-Royce Allison
Siemens Westinghouse Power Company	Solar Turbines
Energy Research Corporation	Rolls-Royce Allison
SOFCo	Northern Research and Engineering Corporation
M-C Power Corporation	Rolls-Royce Allison

<u>21st Century Fuel Cell Program</u>

The 21st Century Fuel Cell Program will develop a new generation of fuel cells with high efficiency and lower costs to meet the increasing demand for electrical energy with the challenge of improved environmental performance. The fuel cell product of the 21st Century Fuel Cell Program will provide the following benefits:

- Stack costs approaching $100/kW and system costs approaching $400/kW.
- Efficiency as high as or exceeding 80 percent (combined cycle).
- Compatible with carbon sequestration and near-zero emissions of other pollutants.
- Wide range of applications: stationary and mobile, large and small scale, central and distributed generation.
- Fuel flexible with multiple future energy options, including hydrogen as an energy carrier.

The key challenge is not simply to increase efficiency by 15 to 20 percent over current developmental systems, but to do so at costs that will provide wider and deeper penetration into a full range for market applications. For very competitive and mature distributed generation markets, at 21st Century Fuel Cell Program must establish new goals which will help realize the full potential of fuel cell technology. With a wide range of applications, the fuel cell product of the 21st Century Program must match efficiency, cost, and performance to the intended market.

FETC is presently developing the plan for the 21st Century Fuel Cell Program. The plan includes initiatives relating to:

- Materials and electrochemistry
- Modeling and virtual design
- Low-cost manufacturing methods
- System definition and testing
- Product manufacture
- Demonstration

Roles are being defined for various groups, including universities, small businesses, national laboratories, and industry. The philosophy of the program is for increased cost share as the design matures such that the demonstrations are funded nearly entirely by industry.

Conclusion

The future of fossil energy based systems is a the intense subject of interest. Fuel cell technology is certain to be a part of our energy future. PAFC systems are being commercialized in part through the support of the Climate Change Fuel Cell Program. MCFC and SOFC systems are planned to enter the market during 2002-2005. Farther into the future, the DOE/Fossil Energy Fuel Cell Program will develop hybrid systems and 21st Century Fuel Cells that promise to improve efficiency and performance at lower cost.